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FIRST WEATHER WING

TECHNICAL NOTE

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TROPICAL CYCLONE INTENSITY ESTIMATION

BY USING

THE DVORAK TECHNIQUE WITH VISUAL SATELLITE IMAGERY

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December 1981

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This technical publication has been reviewed and is approved for publication.

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In 1975, V. Dvorak published a technique for estimating the current intensity of tropical cyclones by using satellite imagery. Measurement of certain cloud features indicate current wind speeds. A "model" development theory and picture clues contribute information on past and future trends. Dvorak's latest revisions are discussed and the current operational procedures for use with visual imagery are offered.

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PREFACE

First Weather Wing Pamphlet 105-10 (Jan 69) was the first document to detail the use of satellite data in the analysis of tropical cyclones in the Pacific. Because of technological and methodological advances, 1WW Pamphlet 105-10 was rescinded in the summer of 1981. The pamphlet has been simplified and divided into five separate publications in order to facilitate use by inexperienced field analysts.

This note (TN-81/001) concerns estimation of the intensity of tropical cyclones with the Dvorak technique. It fits with 1WW audiovisual seminars 79-1B and C in the training program for new personnel. In the remainder of the package, 1WW FM-81/003 addresses development potential of tropical cloud clusters. 1WW FM-81/002 covers locating or positioning cyclones. 1WW TN-81/003 considers data location errors related to spacecraft geometry; 1WW FM-81/004 pertains to gridding techniques. Units may wish to include with their Block 5D Operating Procedures, DMSP User's Guide, and AWS TR212. Suggestion for improvement are welcome.

INTRODUCTION

This technical note considers the technique of estimating the intensity of tropical cyclones based solely on satellite images of the cyclone's cloud system. The technique was developed by Vern Dvorak, (1975) and is currently the only such system in Pacific use.

The Dvorak technique is recognized worldwide as the best available tool for estimating tropical cyclone intensity from satellite imagery alone. However, the Dvorak technique is and has been an evolving system based on accumulated experience. Each storm season adds to the record and often elicits refinements in Dvorak's specific operational rules. Such refinements do not invalidate earlier versions of the system, but promote more reliable results. Accordingly this tech note will summarize Dvorak's system up to the time of this writing. 1st Weather Wing Aerospace Sciences Branch will provide timely field access to Dvorak's later operational refinements as require.

BACKGROUND

The Dvorak system evolved from analyzing images taken during daylight by the earlier TIROS series polar-orbiting satellites. These satellites passed an earth location only once during daylight and once at night. Since Dvorak's early work considered visual data only, the system developed as a 24-hour "picture pair" comparison. Perhaps it was fortuitous, but "tuning" the technique with the animated half-hourly images from later geo-synchronous satellites, has suggested that Dvorak's "24-hour picture pair" decision has actually done more than the expected minimization of diurnal effects. It has demonstrated the value of Dvorak's empirical "model" of tropical cyclone development, which both guides and constrains the image interpretation.

Although each single image received on a given day in a cyclone's life cycle may not yield a perfectly consistent measurement of its intensity, during those periods when the cyclone's cloud features are misleading, the analyst can rely on guidance from Dvorak's "model." Moreover, most single images of most storms will yield accurate intensity estimates. Today the basic premise of Dvorak's system still remains: the cloud features of a tropical cyclone can be used to determine its current intensity when they are analyzed in the context of the cyclone's past history.

Originally the system was a three part operation with each of the three parts weighted equally in determining the final intensity of the cyclone. Those three separate intensity estimates were (and still are) obtained from:

a. Extrapolation along Dvorak's model development curves after qualitatively determining the past 24 hour intensity trend.

b. Comparison of the current storm image with idealized patterns or analogues of past storms.

c. Physical measurements of the cloud features in the current image.

Evolution of the Dvorak system has placed growing emphasis on the measurements of part (c) above. In fact, in the current version, the model (a) and pattern (b) estimates play a very minor role in the final intensity estimate when the storm's cloud features and its growth rate are within defined limits.

This move to quantify or remove subjectivity from the analysis procedure has been greatly aided by Dvorak's recent use of specially enhanced infrared (IR) images. These images depict the tropical cyclones like layered topographic charts. Various gray shade bands offer distinct "edges" from which to measure cloud features. Although cloud features vary significantly from storm to storm, these quantified edges remain. Unfortunately Dvorak's

special IR enhancement curve requires measurements of temperatures colder than the -63°C limit of sensor range in the current generation of DMSP satellites* and their associated electronic processing equipment.

However, since the mechanics of the measurement technique are nearly identical when using either visual or IR data, the discussion which follows will be restricted to visual data. Some comments on how current field forecasters should handle the IR or thermal data will be made later.

DESCRIPTION

To obtain an estimate of the wind speed of a tropical cyclone using the Dvorak technique actually requires analyzing the cloud features three times**. In the first analysis, the cyclone's current intensity is determined by physical measurement of pertinent cloud features. In the second, a qualitative judgment is made as to whether the cyclone has developed, weakened, or remained the same over the previous 24 hour interval. This enables characterizing the cyclone according to Dvorak's model as a rapid, average, or slow changing system. Third, indications seen in the cloud features which relate to ongoing change are assessed. This judgment, when combined with indications from the previous two analyses, allows the meteorologist to <u>forecast</u> tomorrow's intensity. Due to the lack of theoretical basis for Dvorak's empirical development model and the usual "conventional" or "aircraft data to supplant the satellite-derived

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*Dvorak's hurricane enhancement curve, the "BD" curve, is generally available only to customers who are "tapped in" to the GOES data at NESS Satellite Field Service Stations. These stations receive the special photographs relayed from the producing computers in Washington DC.

**The discussion which follows draws heavily on 1WW Seminar 79-1B, Application of the Dvorak Technique," and Dvorak's unpublished "Training Notes," Spring 1980.

intensity estimates, field analysts in Dvorak's parent National Earth Satellite Service (NESS) generally confine their effort to estimating today's intensity. Nevertheless, the essential rules for the forecasting side of the technique are inherent in the analysis procedure and thus always available if needed by analysts.

Nomenclature.

The key to success with Dvorak's system is complete familiarity with his nomenclature. The most important terms follow.

T: (for tropical) is a number from one to eight which is identical to the current intensity (CI) number except when cyclones are weakening. Then, inertial effects usually produce a higher CI (related to wind speed below) than would otherwise be indicated by measurement of the deteriorating cloud patterns.

Figure 1 illustrates the basic intensity relationship showing Dvorak's 0.5 "T" or CI number steps along with corresponding values of maximum sustained wind and minimum sea level pressure. This compilation represents a slight Western Pacific modification to Dvorak's current table.

CI NUMBER	MWS (Kts)	MSLP (Atlantic)	MSLP (Pacific)
0	25	N/A	N/A
1 or 1.5	25	1010 mb	1004 mb
2	30	1007	1001
2.5	35	1003	997
3	40	998	992
3.5	50	993	987
4	60	988	982
4.5	72	979	973
5	85	970	964
5.5	97	960	954
6	110	948	942
6.5	122	934	928
7	135	920	914
7.5	150	906	900
8	170	891	885

Figure 1. Current Intensity, Maximum Wind Speed, and Minimum Sea Level Pressure (After Dvorak).

T numbers are further subdivided into Model-Expected T's (MET), Pattern T's (PT), Data T's (DAT), and Final T's (FT).

<u>MET</u>. The MET is the T number expected today based on yesterday's final T number and extrapolation along one of Dvorak's Model curves shown below.

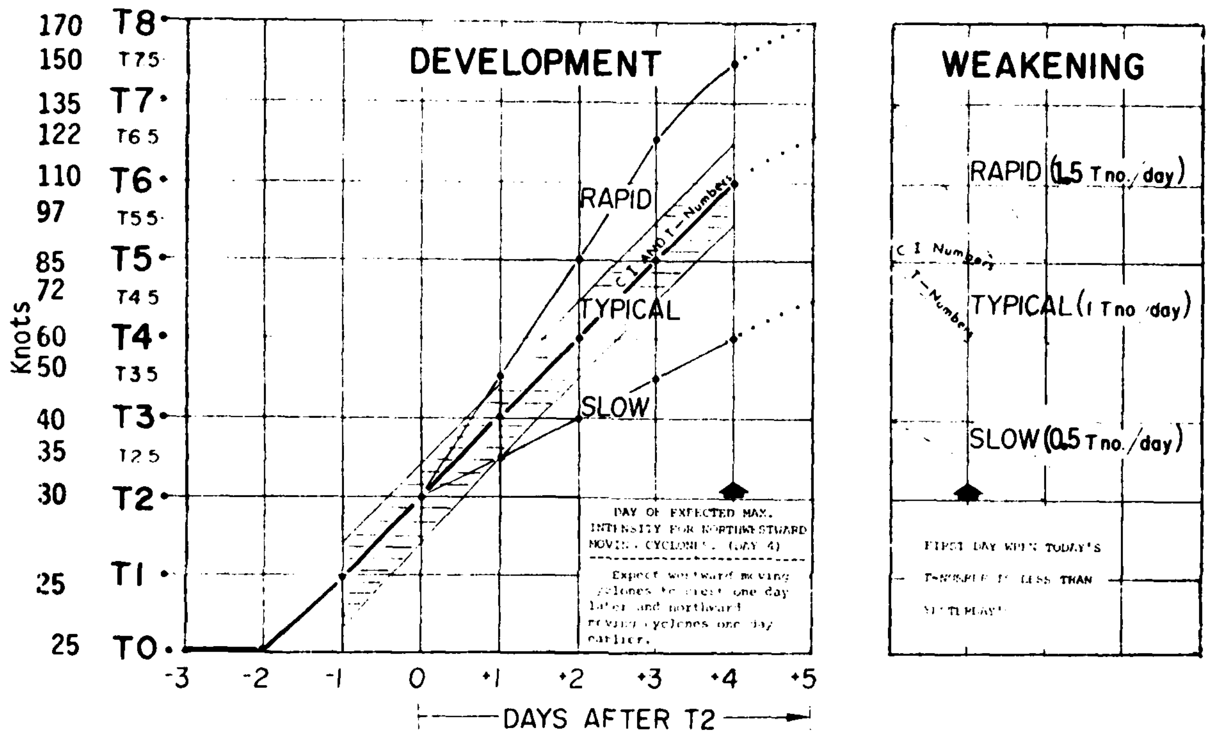

Figure 2. DVORAK'S MODEL OF TROPICAL CYCLONE CHANGE

The curves show that Dvorak's model includes three classes of cyclones. The typical or average (A) cyclone changes by 1.0 T number per day (or 0.25 T number per 6 hours). The Rapid (R) and Slow (S) cyclones change by 1.5 and 0.5 T numbers per day, respectively. When a change rate has not been established in the case of new developments or trend reversals, an average rate of change is always assumed. Cyclones may (and often do) shift from

one curve to another during their life spans. Extrapolation along these curves also enables the analyst to forecast future intensities as required and thus tomorrow's MET usually corresponds to the CI forecast for tomorrow.

PT. The Pattern T is the T number implied by qualitatively "best fitting" the current imagery to one of Dvoraks's idealized pattern analogues. Samples of the patterns are shown in the Appendix.

DT. The Data T is the T number resulting from the actual measurement of cloud features in an image according to the simple procedures in Dvorak's flow chart. The latest version of the flow chart is displayed in the Appendix. This is the heart of Dvorak's system and is covered extensively in 1WW Seminars 79-1B and 1C. The DT is composed of contributions from Central Features (CF) and Banding Features (BF).

CF. Central Features are defined by either the characteristics of the innermost curved clouds and/or the features of the central dense overcast (CDO)* and, if present, the eye itself. The characteristics used range from the size, shape, and distinctness of the CDO and eye, to the distance to the eye from the edge of its parent CDO. (Deeper imbedding denotes stronger cyclones.)

BF. Banding Features reflect contributions to overall cyclone intensity from cloud features outside, and separate from, those already used in determining the CF. When continuous (or nearly so) lines of deep convection of specified width envelope the circulation center, the contribution toward total cyclone strength increases with both the width and the degree to which the bands encircle the circulation center. (An illustration of Banding Feature values is shown below.)

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*The CDO is defined as the dense overcast or "ball" of clouds which comprise the head of the comma within the curvature of the comma-shaped cloud band usually seen in satellite photographs of substantial atmospheric vortices.

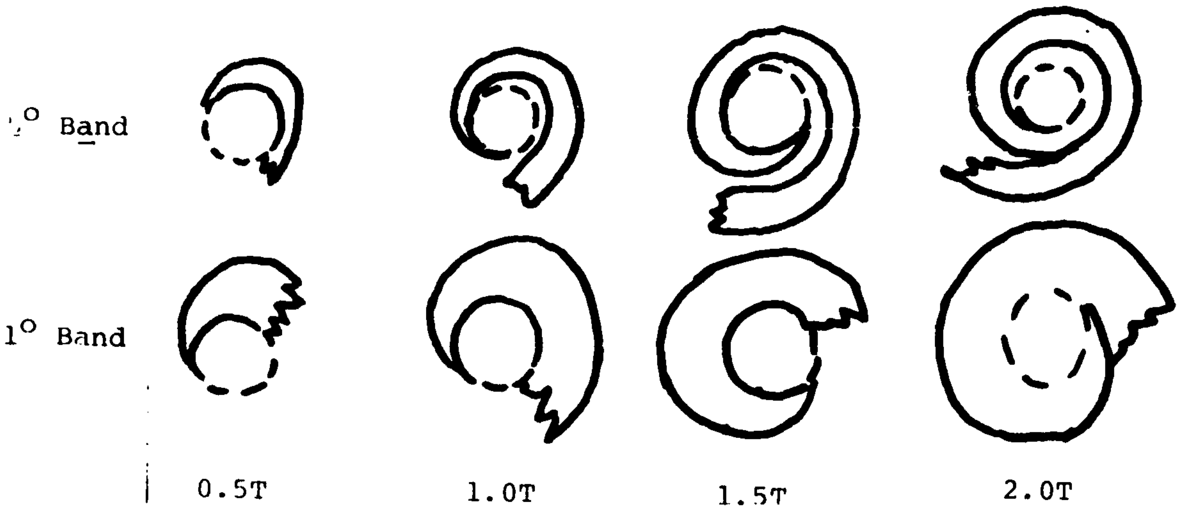

FIGURE 3. T (CI) VALUES OF GIVEN BANDING FEATURES (FB)(After Dvorak) (Dashed Lines Indicate CDO Edges) Scale = 1° Latitude or 60 Nautical Miles)

FT. The Final T, when the Data T is clear and straight forward, is identical to the DT. Otherwise the FT is determined by specified weighting of the DT, MET, and PT according to availability and clarity of component.

This concludes the nomenclature section.

The latest operational version of Dvorak's system suggests that nearly all cyclones develop as one class in a set of five idealized classes as shown below in Figure 4 below.

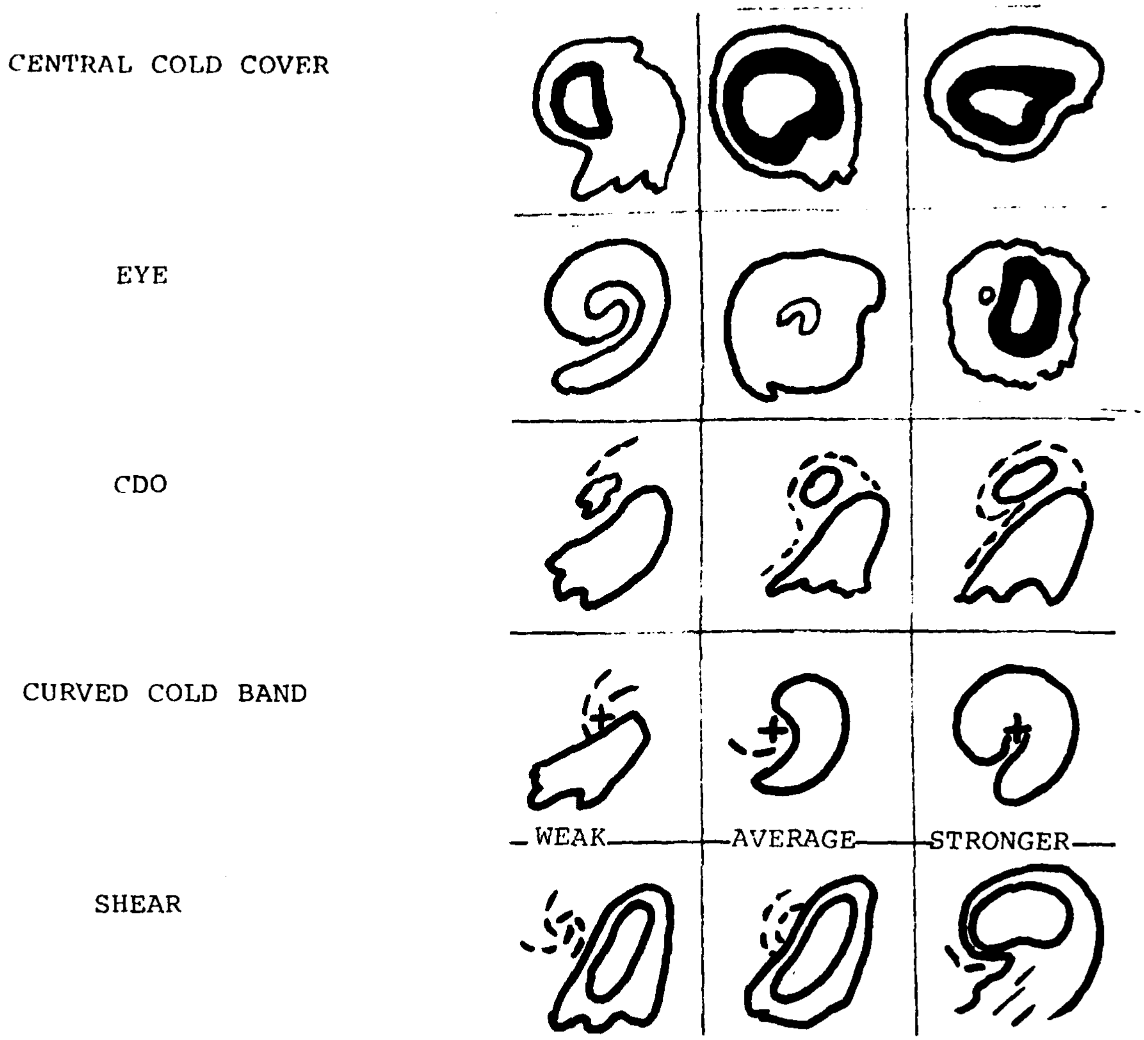

FIGURE 4. IDEALIZED CLASSES OF DEVELOPING TROPICAL CYCLONES
(Coldest temperatures are represented by white inside the black, itself inside the gray area; warmest temperatures are found in the white outside the gray area. The cross (+) is the circulation center.)

Elements of the cloud features exhibited here are measured quantitatively according to Dvorak's flow chart in the Appendix to yield T and CI which, as previously noted, are directly relatable to maximum surface and minimum sea level pressure in the cyclone.

Determining Current Intensity

The first part of Dvorak's three part scheme involves the quantitative

determination of the Data T by means of measuring the cloud patterns as directed by the Flow Chart in the Appendix. Following that two additional qualitative analyses are required. First, the cloud features must be assessed qualitatively to determine how the overall cyclone has changed in the past 24 hours. Has it developed (D); remained the same (S); or weakened (W)? When an eye or definite center is visible, development (D) of central features (CF) has occurred if:

a. The eye is more distinct, rounder, smaller, or defined by more tightly curved banding.

b. More dense overcast is closer to the center or, the center is more deeply imbedded in the overcast.

When the center is covered by dense overcast and is therefore not discernible, development has occurred if:

a. CDO shape has changed from irregular to more angular and/or from angular to more rounded or distinctly-edged.

b. CDO has become larger (while purity of shape is maintained).

Development in banding features (BF) is indicated when banding (composed of essentially continuous lines of well-developed thunderstorms) is wrapped farther around the center; is wider; or is deeper and/or more continuous (less weak spots).

Overall weakening (W) has occurred when the observed changes counter those listed above for development (D). When indications are about balanced, a steady state or remains the same (S) is appropriate.

The evolutionary pattern most often observed in developing tropical cyclones is shown in the "Curved Band," row 4, of Figure 4. From left to right, note that the band curves farther around the disturbance center as the cyclone develops. The dense clouds making up the "cold curved bands"

are defined as those whose temperatures are colder than -30°C. The intensity of a disturbance displaying this type of cloud pattern is directly related to the degree of encirclement of the center of the cloud system by the dense cold band. When the cyclone evolves to hurricane strength, the band is observed to completely encircle the cyclone center forming one of the "eye" patterns shown in row 2. Continued intensification past hurricane strength is usually indicated by the clouds encircling the "eye" becoming colder, or by the "eye" becoming either warmer, smaller, or more circular.

Unfortunately, these rather simple indicators of intensity are not observed at all times during a tropical cyclone's life cycle. In the pre-hurricane or decaying stages of a disturbance, vertical wind shear may be sufficient to prevent the cold band from forming or remaining around the cloud system center. When this occurs, one of the "shear" patterns illustrated in row 5 of Figure 4 is observed. These patterns show the cyclone center, defined by the curvature of low (dashed) cloud lines, either out from under, or just under, the edge of a cold, dense cloud mass. The intensity estimate determined from one of these patterns is inferred from the curvature of the lower clouds defining the center and from the center's proximity to the cold dense overcast.

Another complication arises in the analysis when the cyclone undergoes a period of intense convective activity. When this occurs, large, cold cirrus "bursts" may obscure portions of the pattern making the curved band difficult to measure.

In addition to these difficulties, there are other circumstances (discussed under further considerations) when a cyclone's actual intensity may differ from the intensity suggested by its cloud features. Because of these special circumstances, as well as the difficulties that may sometimes

arise in obtaining clear-cut measurements, the final determination of current intensity in the Dvorak technique does not depend solely on measuring the cloud features which determine the Data T. The analysis is always performed in the context of Dvorak's empirical model of tropical cyclone development.

In addition to providing overall guidance for the analysis, the model also (1) places absolute limits on the rate of change of T numbers with time; and (2) specifies, when cyclones are weakening, the amount by which the decaying cloud patterns usually underestimate the cyclone's strength; and (3) furnishes two more estimates of intensity, the MET and the PT, to provide a backup for the quantitative (DT) estimate whenever it is unclear.

After the current intensity of the tropical cyclone is determined from its current image and the analyst has decided on a past trend, he/she has the further option of making a 24-hour intensity forecast. In order to do so simply extrapolate the past rate of intensity change into the future or, when appropriate indications appear in the cloud features, modify tomorrow's estimate up or down, according to rules in the flow chart in the Appendix.

Indications of Ongoing Change

The second and final qualitative analysis in Dvorak's scheme seeks to assess the cyclone's future trends by using current and past images. Indications of ongoing development appear in the image when the cyclone maintains strong low level inflow of warm moist air, coupled with continued outflow aloft. The trajectory and strength of low level inflow can often be inferred by alignment, curvature, and convective strength of the cumulus bands which spiral into the storm center. Upper outflow is similarly inferred from cirrus patterns over the storm. For instance, if

the fuzziness, radiality, and anticyclonic curvature of cirrus increases, continued development is likely. Rapid development is indicated if two successive (6 hours apart) observations of faster than normal development are seen. The opposite of these characteristics suggests ongoing weakening. Trend abatements or reversals, or both, are generally caused by changes in the cyclone's environment (realizing, of course, that sizeable cyclones often "create their own environment").

Finally, recall that Dvorak's model suggests a chronological life cycle for "average" cyclones. That is, depending on the cyclone's direction of movement, maximum intensity or "peaking" is expected 3 to 5 days after T2.0 strength has been attained. Northward moving cyclones usually peak in 3 days; westward moving in 5 days; and others in 4 days. These rules are evidently a statistical reflection of how soon the "climatological" cyclone usually encounters an unpleasant environment. Some of these damping environments are:

a. Areas of land.

b. Areas of colder water or dry low level air or both (often shown by the presence of stable stratocumulus cloud fields).

c. Areas of strong vertical wind shear (suggested by unidirectional cirrus motion developing along the forward cirrus canopy of the cyclone, or midtropospheric troughing northwest of the cyclone).

Of course the analyst must be alert to reintensification when an otherwise healthy cyclone leaves these environments for others more hospitable.

OPERATIONAL SUMMARY

Vern Dvorak has developed a method of tropical cyclone analysis through the use of satellite photographs. The technique has been shown to be a straightforward method of estimating the intensity of tropical cyclones involving three primary judgments: two qualitative and one quantitative.

The quantitative portion determines the cyclone's current intensity by measuring certain cloud features. These measurements are supplemented, when inconclusive, by indications from Dvorak's "model" of cyclone development and his generalized pattern analogues. One qualitative judgment determines whether the cyclone has developed, weakened, or remained static over the past 24 hour interval. A second qualitative analysis assesses photographic indications of ongoing change. When these three judgments are properly combined, the analyst can forecast tomorrow's intensity.

FURTHER CONSIDERATIONS

Implementation of Dvorak's system by varied, worldwide users has not been without problems. Most of the problems have been addressed by Dvorak and others. Many appear to have been solved. A few still remain.

The first difficulty encountered by DoD operational forecasters at the JTWC arose because of the much better resolving power of DMSP satellite sensors as compared to the resolution seen in the TIROS images Dvorak used to design his system. The finer photographic detail available to the DoD forecaster often suggested breaks in bands or irregularities in cloud boundaries which were glossed over by the coarseness of Dvorak's data. This induced a rather natural uncertainty amongst the analysts. These meteorologists responded by "mentally" smoothing the DMSP data so as to avoid this "failure to see the forest for the trees" syndrome.

In addition, Dvorak's rules, developed for visual data, proved difficult to adapt to IR or thermal images. This was due to the tendency of the brightly-rendered cirrus to obscure, on the IR images, the lower cloud features fundamental to the measurement process. Ironically Dvorak's recent advances (now used operationally in the NESS) have employed these

same IR images as the means to objectify the intensity estimation procedure. Dvorak's latest technique modification, as earlier discussed, involves specially enhanced IR images which provide quantified, storm-to-storm reproducible edges from which to make cloud measurements. Unfortunately, the ability to threshold DMSP thermal images identical to the coldest reaches of Dvorak's storm enhancement curve is not currently available. An approximation may be possible after the 1982 launch of F-6. As experience is gained with Dvorak's infrared procedures, 1WW Aerospace Sciences will issue additional guidance. Use of real-time microwave imagery in the tropical cyclone warning system is another subject likely to be addressed in a future technical note.

In the meantime DoD analysts can continue to photographically process thermal images so as to damp, as far as possible, this "interference" tendency of cirrus. Since measurements taken from thermal images often overestimate cyclone strength (when using the visual image flow chart), analysts attempting to adapt visual rules to IR images should rely more heavily on Dvorak's model development curves. Such reliance has not always proven prudent, because there are times - both day and night - when a cyclone's actual intensity may definitely differ from the intensity indicated by its cloud features. Some of these occasions are:

a. When a cyclone's cloud pattern evolves extremely rapidly (usually during the pre-tropical storm strength stage).

b. When a cyclone is weakening and the deteriorating cloud patterns imply premature reduction in wind speeds.

c. When a significant loss of cloud cover occurs at night, especially in cyclones near continents.

d. When a convective "explosion" releases globs of cirrus which might be mistaken for rapid development but more likely suggest a pause in development.

Rules for addressing problems such as these accompany the basic flow chart in the Appendix. Such exceptions also reemphasize the importance of performing the intensity measurements in the context of Dvorak's model of cyclone development.

In designing the system and in adding its many refinements, Dvorak has attempted to provide a simple, straightforward operation with built in redundancy so that different analysis routes arrive at the same destination --a reliable estimate of cyclone strength. Technique development has resulted in a procedure which can now employ imagery from many different satellites, with a variety of sensor resolutions, for use by analysts of varying experience levels in locations all over the globe. The "bottom line" has always been to produce as consistent and accurate a "fix" as then possible.

A LOOK AHEAD

Even though some have questioned the inherent value of error statistics using subjective "best track" positions and intensities as "ground truth," several investigators have evaluated various aspects of Dvorak's technique. All agree that the technique provides reliable intensity estimates which match "best track truth" within 1.0T number a high percentage of the time. While this accuracy is quite satisfactory at the average intensities seen in the large majority of tropical cyclones, a deviation of one T number from the actual value for a super typhoon threatening a major city would be an error of possibly deadly proportion. The height difference in storm surge generated by a T8 "superstorm" incorrectly estimated at T7 by satellite, would produce serious problems indeed for the responsible warning agency. Further, most investigators and users of the Dvorak technique agree

that (with the possible exception of microwave), near term technological advances in satellite imagers are likely to produce little significant improvement in the satellite analyst's ability to either locate, or estimate the intensity of tropical cyclones.

Such considerations reemphasize the value of the Selective Reconnaissance Program with its ability to direct that aircraft measurements be obtained from tropical cyclones which imminently threaten population centers. Unfortunately, as Dvorak has refined his technique, there has been a significant drawdown in aircraft resources available for tropical cyclone reconnaissance. Under the Selective Reconnaissance Program, satellites have provided an increasing proportion of each year's cyclone fixes. Although aircraft reports are expected to remain essential to the future of the tropical cyclone warning services both within and without the DoD, future budgets are likely to further encourage this "trend-toward-satellite." Therefore, all field forecasters who expect to confront tropical cyclones in their daily assignments should become familiar with Dvorak's procedures.

REFERENCE

Dvorak, Vernon F., 1975:

Tropical Cyclone Intensity Analysis and Forecasting from Satellite Imagery. Monthly Weather Review: 103, pp 420-430.

APPENDIX

STEP-BY-STEP INSTRUCTIONS FOR USING DVORAK'S FLOW CHARTS FOR VISUAL IMAGES

Step 1. Review the history of the disturbance and note its 24-hour old T number and position. Then locate the cloud system center (CSC) or low level circulation center (LLCC). See 1WW TN 81/002, for instructions.

Initial Development. A classification of T1 is first used when a cluster of convective clouds with cirrus has persisted for 12 hours or more having an area of dense, cold (cirrus) overcast* of $1\frac{1}{2}^{\circ}$ of latitude in extent, located less than 2° from a cloud system center which is defined by cloud line or band curvature within an area having a diameter of $2\frac{1}{2}^{\circ}$ latitude or less. Before classifying T1, the center definition must persist for at least three hours. The cloud system center will be defined in one of the following ways:

a. Curved, dense, convective band that curves around a cloud minimum area. It should curve at least $\frac{1}{4}$ the distance around a 10° log spiral. Cirrus, when visible, will indicate anticyclonic shear across the expected CSC (see Step 10, PT 1.5a).

b. Curved cirrus lines indicating a center of curvature within 2° latitude of a dense overcast which has band curvature surrounding it (see Step 10, PT 1.5b).

c. Curved low cloud lines showing a center of curvature within 2° of a convective cloud mass with some convective band curvature around the center (see Step 7, DT 1.5).

- - -

NOTE: The amount of cold overcast may decrease during the subsequent 12-hour period making it crucial that the analyst watch for the required amount of overcast when it occurs.

During the 36-hour period preceding the T1 classification, many Cb groups that develop will show indications of a sharpening or flattening of the poleward boundary of the cloud system. A T1 classification is expected about 12 hours after the cloud system loses its flattened appearance and shows curvature in its cloud lines.

A flat boundary rotating across the poleward side of the pattern throughout the period is a good sign of development. NOTE: A classification of T1 anticipates attainment of tropical storm strength (T2.5) about 36 hours after the T1 observation if the environment remains favorable. A promising satellite technique of evaluating the development potential of tropical cloud clusters is presented by Danielson in 1st Weather Wing Forecaster Memo 81/003.

Step 2. Prepare to choose the applicable analysis step. The past history of the disturbance and the manner in which the cloud system center is currently defined will determine which of the next five steps you should choose.

Step 3. Central Cold Cover (CCC) pattern exists when the cyclone does not reveal the usual signs of evolution because of a "more-or-less" round, dense overcast (glob) which covers the storm center or comma head. When this condition persists, inhibiting a clear indication of pattern evolution, development has probably been arrested until positive signs of development or weakening once again appear in the cloud features. In this case take the following precautions:

a. Do not confuse a central cold cover pattern with a "very cold" pattern. A "very cold" pattern is indicated by a very dense, smooth-textured comma tail and head with some indication of a wedge in between.

Curved cirrus lines or boundaries usually appear around the "very cold" pattern and not around the CCC pattern. The "very cold" pattern in young cyclones often indicates rapid growth and is likely to warrant an additional ½ T number in intensity estimate.

b. Do not assume weakening has begun when the comma tail begins to decrease in size or when the CCC begins to warm or thin. It is common to observe the tail decreasing in size at the onset of a "CCC burst." Also the CCC often thins as the eye of the T4 pattern begins curving into the side of the cold overcast as the cyclone resumes its development.

<u>Step 4</u>. "Eye" patterns are analyzed in this step <u>only</u> when they are observed at least 24 hours after the system has been classified at T2 or greater. Another requirement is that the eye fall near the point of the expected cloud system center. The analysis of the eye pattern involves three computations:

a. The "E" (eye) number.

b. The eye adjustment factor (Eye Adj).

c. The banding feature (BF) adjustment.

The equation is: E + Eye Adj + BF = DT (Data T Number).

a. The E number is obtained by measuring the distance the eye is imbedded in dense overcast clouds. The imbedded distance of the eye is measured outward from the center of the eye to the nearest point on the outside edge of the dense overcast for small (30 nm) round eyes. For all others, measure outward from the inner wall of the eye. When a banding type eye is indicated, use the average width of the band surrounding the eye.

The eye adjustment factor is determined by the definition, shape,

and size of the eye. To be well defined, the eye should be wholly dark or black. Remember that a low sun angle may reduce the eye definition. A poorly defined eye is one that is barely visible or cloud covered. A ragged eye is one with a very uneven boundary and thus little circularity. A large eye is one greater than or equal to $3/4^{o}$ latitude in diameter. The eye adjustment rules are summarized on the first page of the flow chart.

c. The banding feature adjustment (BF) is required when a dense, mostly overcast convective band curves quasi-circularly at least ¼ the distance around the central feature. Bands that curve evenly around an inner BF may also be counted out to about 4^{o} from the CSC. The "T" value assigned the BF term depends on the width of the band and the amount that it curves evenly around the central features. See the table in the flow chart. A BF adjustment is not used for pre-hurricane patterns when Step 6 is employed. However, it is used for CDO patterns (Step 5) and for other hurricane or stronger patterns as indicated.

Step 5. CDO patterns are defined when a dense mass of clouds covers the cloud system center and lies within the curve of the system's comma band. Both CDO size and the sharpness of its boundary are important to the analysis. A well defined CDO has an abrupt edge in at least one quadrant of the cloud mass. An irregular CDO has ragged boundaries. The size-CF number relationship is given in Step 5 of the diagram.

Step 6. "Curved Cold Band" patterns are primarily associated with the pre-hurricane stages of cyclone development. A band showing little curvature is often observed at the pre-storm stage (T1.5 illustration in Step 6). As intensity increases, the band curls farther around the cloud system

center. In visual images the band appears mostly overcast with cirrus lines often giving it form. It will usually have some strong CB cells along its central axis. The intensity estimate determined from this pattern type is arrived at by measuring the distance the band curves around a 10^{o} logrithmic spiral overlay fitted to the comma band's axis of curvature. The fraction of complete encirclement is the key indicator. The comma axis of curvature is defined as the axis of the most dense clouds in the comma band. Cold "globs" that miss the exact axis should be ignored when drawing the line, but the axis should be extended on through the CDO when one is present.

In some patterns the cold comma band will often show warm breaks through its middle. These breaks will appear to be almost clear in the "VIS" picture. When this occurs, draw the comma axis as though it were continuous through the breaks.

During the T2.5 to T3.0 stage, an inner, more tightly-curved, cold band axis is also often observed. This inner comma tail usually forms the tighter (under 1.25^{o} dia) curvature indicative of tropical storm intensity.

Step 7. "Shear" patterns appear in the weaker stages of both developing and decaying storms when strong upper level flow prevents the cold clouds from wrapping around the cloud system center as in Step 6. In the shear pattern, curved lines of low clouds indicate a center of curvature near the edge of an abrupt cloud boundary (strong temperature gradient).

The intensity estimate determined from this pattern type is arrived at by:

a. The way in which the cloud system center is defined.

b. The relationship of the low cloud center to the dense, cold

overcast. Near the T2.0 intensity stage the low cloud center will either be poorly defined in spiral lines near a cold overcast; circularly defined, but some distance (> 1.25° lat) from the standard ($\sim 2^{\circ}$) sized cold overcast clouds; or circularly defined near a lesser amount (< $1\frac{1}{2}^{\circ}$ diameter) of dense overcast.

For patterns associated with tropical storm intensities (T2.5 to T3.5), the center will be defined in parallel, tightly-curved low cloud lines, either near or under the edge of a dense, cold overcast cloud mass with a diameter of at least $1\frac{1}{2}^{\circ}$ latitude.

Step 8. Qualitatively determine the trend of the past 24-hour intensity change by comparing the cloud features of the current picture with those of the 24-hour old picture of the storm using the indicators listed in the text.

Step 9. The model expected T-number (MET) is determined by using the 24-hour old T-number, the D, S, or W decision in Step 8, and the past rate of intensity change of the storm. Average (A) storms change by 1.0T number per day: rapid (R) by 1.5T; and slow (S) by 0.5T.

When a rapid or slow past rate of change has not been established by two consecutive pattern analvses of 6-hour or more intervals, use one T-number per day change. For new cyclones assume average development until the trend is clear. Cyclones can and do change from one development or decay curve to another.

Step 10. The selection of a pattern T-number (PT) is made by choosing the pattern that best matches your image of the cyclone. Enter the flow chart in the PT column suggested bv the MET, and select your PT from that column

or the column on either side of it. This step is used primarily to check the analysis already made using the previous steps. If you've been unable to choose from Steps 3 through 7, Step 10 can sometimes suggest a pattern which will allow you to return to one of them. If not, the Step 10 PT can be used along with the MET to obtain the T-number when necessary. See rules in the Step 11 box.

Step 11. This step states the rules for determining the final T-number from either the data T-number (DT) or from the pattern T-number (PT) and the model expected T-number (MET), depending on which step was used in the analysis. When no step of the flow diagram appears to apply to your storm, use the MET itself as the T-number.

Step 12. This step, particularly useful to inexperienced analysts, provides that the final T-number must fall within the restraints listed in the box. In other words, when your T-number does not fall within the stated limits, you must adjust it to comply with these limits.

Step 13. The current intensity (CI) number relates directly to the strength of the cyclone. The empirical relationship between the CI number and a cyclone's wind speed is shown in the text.

The CI number is always the same as the T-number during the development of a tropical cyclone, but is held higher than the T-number while a cyclone is weakening. This is done because a lag is often observed between the time a cyclone's cloud pattern indicates weakening has begun and the time a cyclone's intensity actually decreases. An added benefit from this rule is the stability it adds to the analysis when short period fluctuations in the cloud pattern occur. This is particularly useful in these days of frequent

image availability from multiple satellites. In practice, the CI number is not lowered until the T-number has shown weakening for 12 hours or more. The CI number is then held one number higher than the T-number for rapidly weakening cyclones; 0.5T higher for average cyclones; and the same as the T-number for slowly weakening cyclones.

Step 14. The 24-hour intensity forecast is an extrapolation of the persistent trend unless indications in the satellite imagery of ongoing change suggest this would be imprudent.

The indications of ongoing change combined with the model development curves in the text will indicate what tomorrow's T/CI number is likely to be. Subjective adjustments cannot deviate by more than $\pm$ 1.0T number from the T forecast indicated by extrapolation along the appropriate model curve. Whenever your forecast diverges from that predicted by Dvorak's model append appropriate explanation to your fix message.

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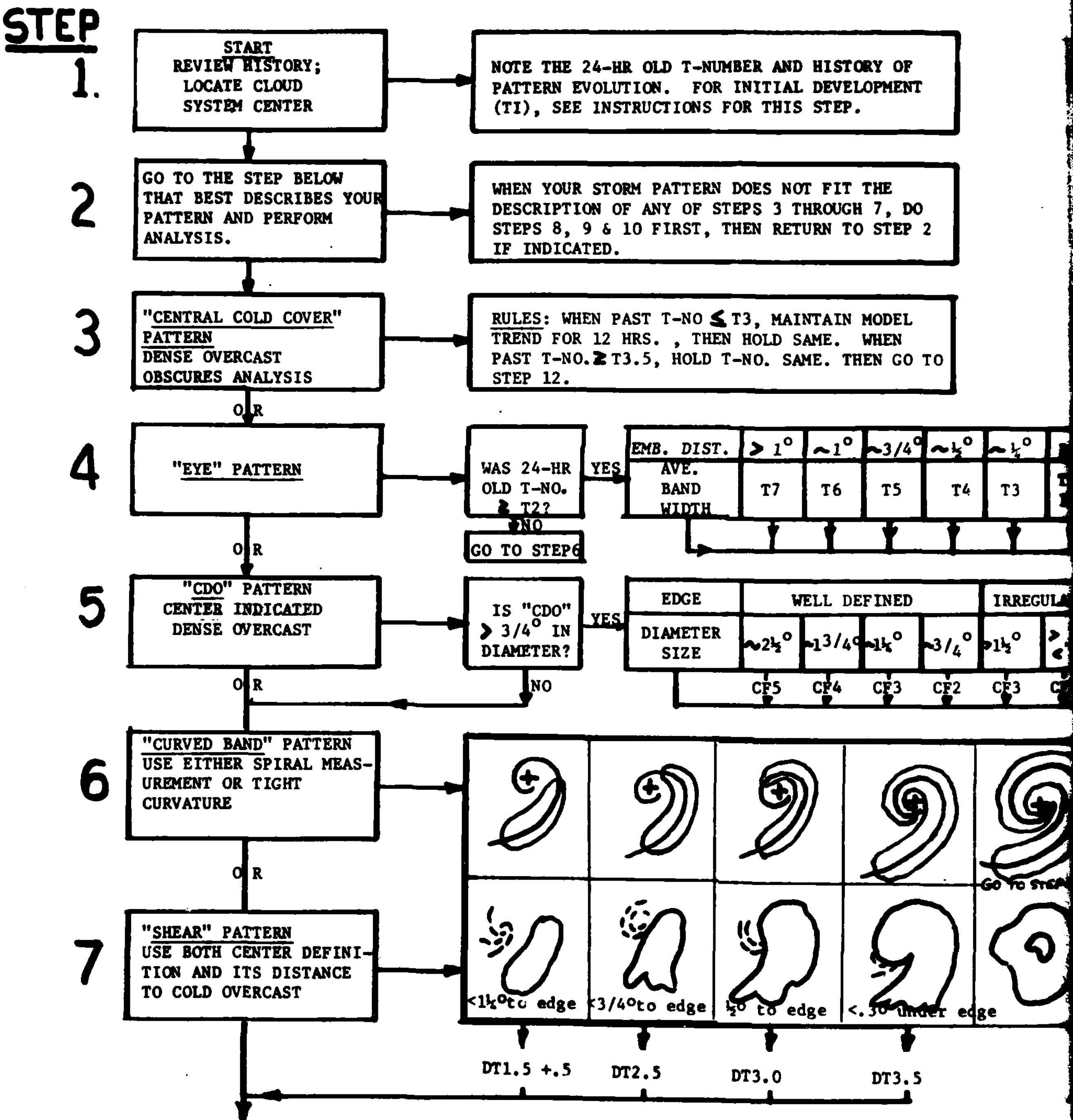
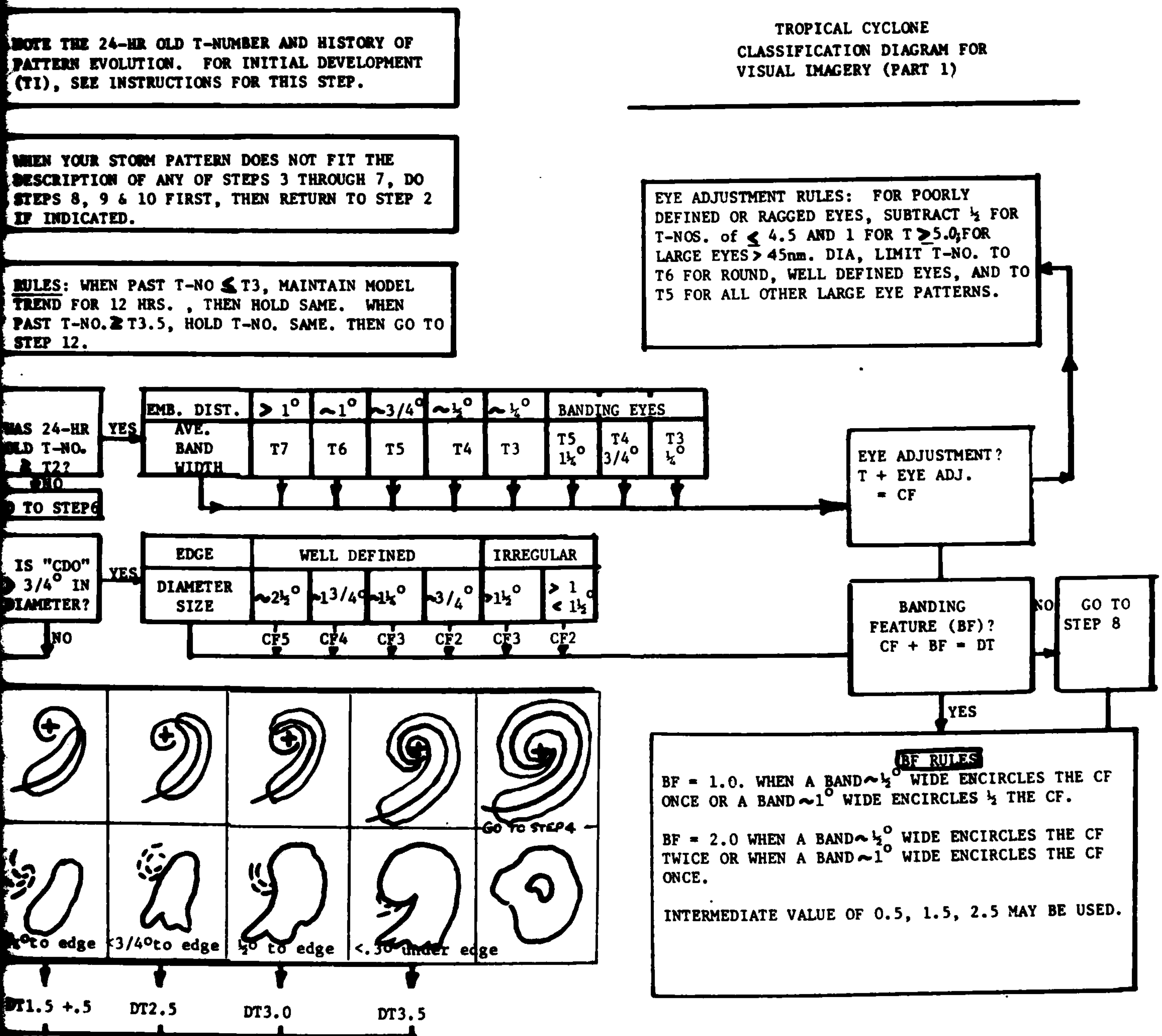
NEPRF	5
AFGL	5
USAFETAC/TS	5
3350 TCHTG/TTMV-F	10
Det 4, HQ AWS	2
AFGWC/NESS LIAISON	10


STEP
1.
START
REVIEW HISTORY;
LOCATE CLOUD
SYSTEM CENTER
NOTE THE 24-HR OLD T-NUMBER AND HISTORY OF PATTERN EVOLUTION. FOR INITIAL DEVELOPMENT (TI), SEE INSTRUCTIONS FOR THIS STEP.
2
GO TO THE STEP BELOW THAT BEST DESCRIBES YOUR PATTERN AND PERFORM ANALYSIS.
WHEN YOUR STORM PATTERN DOES NOT FIT THE DESCRIPTION OF ANY OF STEPS 3 THROUGH 7, DO STEPS 8, 9 & 10 FIRST, THEN RETURN TO STEP 2 IF INDICATED.
3
"CENTRAL COLD COVER" PATTERN
DENSE OVERCAST OBSCURES ANALYSIS
RULES: WHEN PAST T-NO ≤ T3, MAINTAIN MODEL TREND FOR 12 HRS. , THEN HOLD SAME. WHEN PAST T-NO. ≥ T3.5, HOLD T-NO. SAME. THEN GO TO STEP 12.
OR
4
"EYE" PATTERN
WAS 24-HR OLD T-NO. ≥ T2?
YES
NO
GO TO STEP6
EMB. DIST.
AVE. BAND WIDTH
> 1°
~1°
~3/4°
~½°
~¼°
T7
T6
T5
T4
T3
OR
5
"CDO" PATTERN
CENTER INDICATED
DENSE OVERCAST
IS "CDO" > 3/4° IN DIAMETER?
YES
NO
EDGE
WELL DEFINED
IRREGUL
DIAMETER SIZE
~2½°
~1 3/4°
~1¼°
~3/4°
>1¼°
CF5
CF4
CF3
CF2
CF3
OR
6
"CURVED BAND" PATTERN
USE EITHER SPIRAL MEASUREMENT OR TIGHT CURVATURE
OR
7
"SHEAR" PATTERN
USE BOTH CENTER DEFINITION AND ITS DISTANCE TO COLD OVERCAST
<1¼° to edge
<3/4° to edge
½° to edge
<.3° under edge
DT1.5 +.5
DT2.5
DT3.0
DT3.5

TROPICAL CYCLONE
CLASSIFICATION DIAGRAM FOR
VISUAL IMAGERY (PART 1)



1

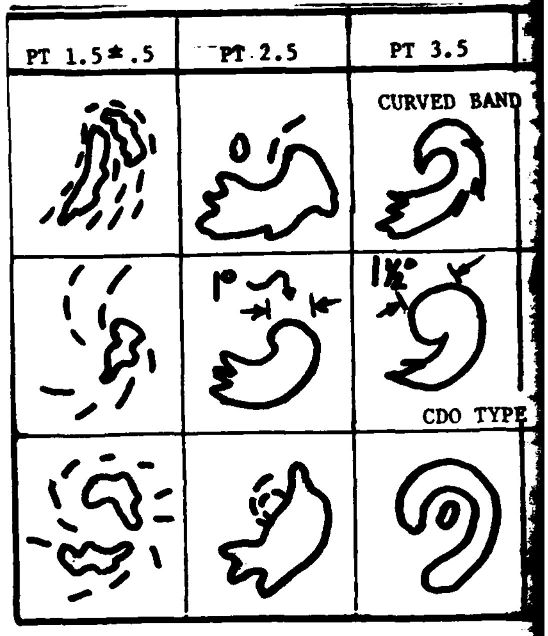
2

8 DETERMINE PAST 24-HR TREND. IS DEVELOPMENT, WEAKENING, OR THE SAME INDICATED BY A CHANGE IN EITHER:

a. CENTER OR EYE CHARACTERISTICS,
b. OR CENTER"S INVOLVEMENT WITH COLD (DENSE) OVERCAST

9 DETERMINE MODEL EXPECTED T-NO. (MET)

10 SELECT PATTERN IN DIAGRAM THAT BEST MATCHES YOUR STORM PICTURE WITHIN ONE COLUMN OF THE MET.



WHEN CLOUD CO
(< 2½° LAT), S

11 **T-NUMBER DETERMINATION:**

FOR STEP 4,5,6,7 WHEN CLEARCUT, USE T = DT. FOR STEPS 4,5,6,7, WHEN NOT CLEAR, USE $T = \frac{DT + MET}{2}$

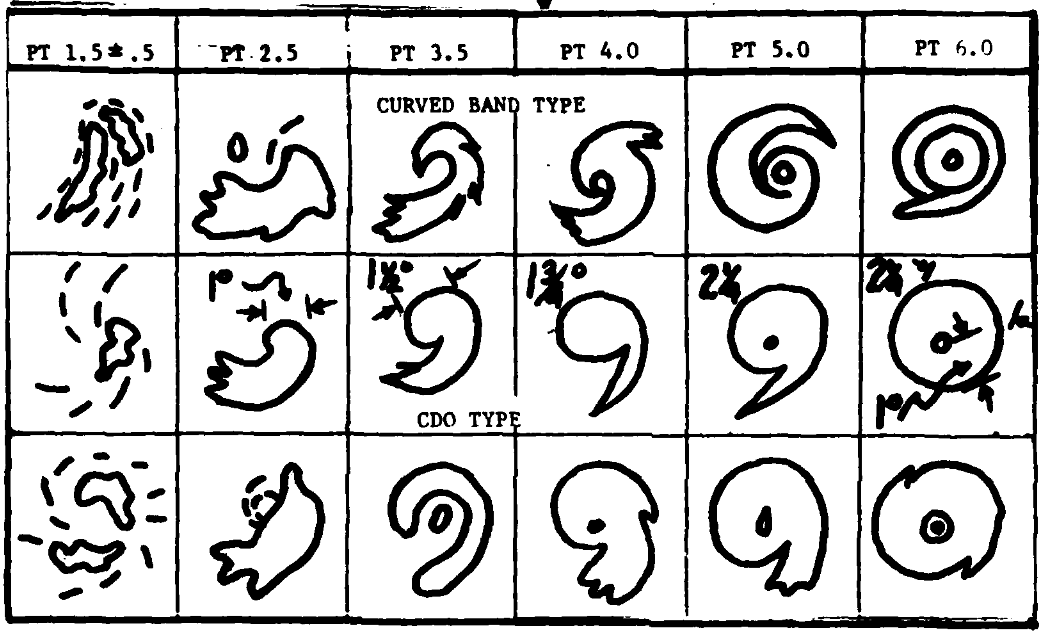
FOR STEP 10, USE $T = \frac{PT + MET}{2}$

FOR OTHERS, USE T = MET, ROUND OFF NUMBERS TO NEAREST .5 T-NO. TOWARD MET.

FINAL T-NUMBER CONSTRAINTS:

1. INITAL CLASSIFICATION MUST BE T1 OR T1.5 (T1 FOR 6-HR OBS.
2. 24 HRS AFTER INITIAL T1, STORM'S T-NO. MUST BE ≤ T2.5.
3. DURING FIRST 48 HRS OF DEV. T-NO. CAN"T BE LOWERED AT NIGHT.
4. FINAL T-NO. MUST = MET ±1.
5. FINAL T-NO. MUST BE ≤1 FROM 6-HR OLD CLASSIFICATION.

12



WHEN CLOUD COMMA IS EXTREMELY SMALL (< 2½° LAT), SUBTRACT 1 FROM PATTERN NUMBER

FINAL T-NUMBER CONSTRAINTS:

1. INITAL CLASSIFICATION MUST BE T1 OR T1.5 (T1 FOR 6-HR OBS.
2. 24 HRS AFTER INITIAL T1, STORM'S T-NO. MUST BE ≤ T2.5.
3. DURING FIRST 48 HRS OF DEV. T-NO. CAN"T BE LOWERED AT NIGHT.
4. FINAL T-NO. MUST = MET ±1.
5. FINAL T-NO. MUST BE ≤1 FROM 6-HR OLD CLASSIFICATION.

12

CURRENCY INTENSITY (C.I.) NUMBER RULES:

1. USE C.I. = FINAL T EXCEPT WHEN FINAL T SHOWS CHANGE TO WEAKENING TREND.
2. FOR INITIAL WEAKENING HOLD C.I. SAME FOR 12 HRS THEN HOLD C.I. ½ OR 1 HIGHER THAN T AS STORM WEAKENS.

13

24-HOUR FORECAST

EXTRAPOLATE PAST TREND UNLESS MODIFICATION AS DISCUSSED IN THE TEXT UNDER "INDICATIONS OF ONGOING CHANGE" IS REQUIRED

14

LMED

8